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Hierarchical Models of the Nearshore Complex System: Final Report

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The long-term goal of this research was to develop and test predictive models for nearshore processes.

OBJECTIVES

This grant was termination funding for the Werner group, specifically aimed at finishing up and publishing research related to synoptic imaging of nearshore bathymetry, testing models for beach cusp formation and modeling sand bar evolution.

APPROACH

Computer simulations, theory and field observation, experimentation and monitoring are combined to formulate, develop, test and refine models for nearshore dynamics

The underlying assumption of this research is that models for nearshore processes should reflect their nonlinear, open and dissipative nature, which selects and orders variables and processes through collective self-organization. One form of variable selection in the nearshore and many other nonlinear systems is spatial localization of dynamics, owing to collective nonlinear interactions. Examples of such localization include breaking wave fronts, offshore currents localized into rips and focused bathymetric change at shorelines or sand bars. In addition, variables at different temporal scales do not interact symmetrically. This well-studied property of nonlinear, dissipative systems stems from the tendency of fast temporal scale motion to be dissipated over longer time periods. For example, the fast, but dissipative motion of a sand grain in a more sluggish offshore migrating sand bar is slaved by or follows the bar.

The traditional Reductionist Approach (fundamental physics/equations) fails for natural systems such as the nearshore because of a lack of defensible criteria for selecting dynamical variables. The necessity that all dynamics stems from the fundamental scales and processes in Reductionism conflicts with the asymmetrical interactions between scales for nonlinear, dissipative systems, with the larger, longer scales being dominant. Universalist approaches (using the simplest system in a class of systems sharing common behaviors to model the entire class) fail because the simplifying assumptions underlying Universalist models necessarily imply an inability to treat the variability and complexity inherent in the natural environment (external to the system being studied).

A new, hierarchical modeling methodology is meant to address these criticisms of Reductionism and Universality. It can be summarized with the following four steps:
(i) delineate the boundaries of the open system;

(ii) identify and temporally order dynamical variables of the system and variables in the external environment affecting system dynamics;
(iii) at each level in this temporal hierarchy, encapsulate the dynamics of faster variables into minimal rules that relate the evolution of variables at this level to each other and to the external environment;
(iv) formulate models at each level and derive testable predictions of the models.
(v) test the theoretical consistency of the modeling hierarchy by comparing predictions for a phenomenon from models at two different levels (thereby enhancing the testability of the models).

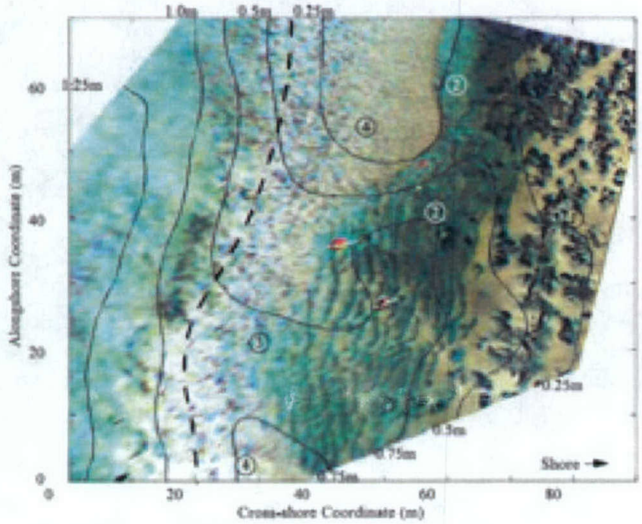
This methodology is distinguished from Reductionism and Universality primarily by modeling phenomena at their intrinsic time scales. For example, to model motion of a sand bar, the variables appearing in the model describe that motion (e.g., sand bar position and height), not positions of sand grains, nor the flux of sand nor water motions over the bar, all of which have much smaller intrinsic time scales and are expected to be slaved to the motion of the bar.

WORK COMPLETED
¥ a paper describing the synoptic imaging technique and tests was completed and published.
¥ a paper describing a model for megaripple occurrence in the surf zone was written and published.
¥ a paper describing observations of megaripple orientation and tests of two models for bedfrom orientation in the surf zone was writtten and awaits publication.
¥ a paper describing tests of a self-organization model for beach cusp formation was published.
¥ a paper describing the effect of tides on beach cusp development and comparisons to a numerical model was written and published.
¥ a model for multiple sand bar formation and migration was developed.

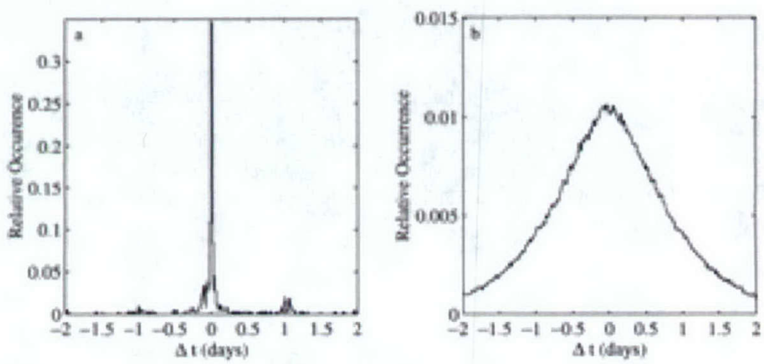
RESULTS
For the synoptic imaging technique (Clarke and Werner, 2003), video frames acquired from a camera viewing the surf and swash zones from a cliff are downloaded to a workstation, processed to remove pixels from breaking waves or foam, averaged over a period of several minutes and false-color-enhanced to emphasize bathymetric features. Depending on conditions and field of view, crests of bedforms including megaripples, sand bars, rip channels, and sediment and cobble transport patterns can be extracted. Resolution is degraded by large waves, sediment-laden or bio-fouled water and glare. This technique was used to acquire continuous images of nearshore bathymetric patterns (at 5-10 minute intervals) during daylight hours on Scripps Beach.

This technique is one component of an effort to monitor the connection between sediment and bathymetry outside the surf zone and bathymetry and bathymetric patterns within the surf zone. It permits views of both small and large scale features, such as megaripples and sand bars, as

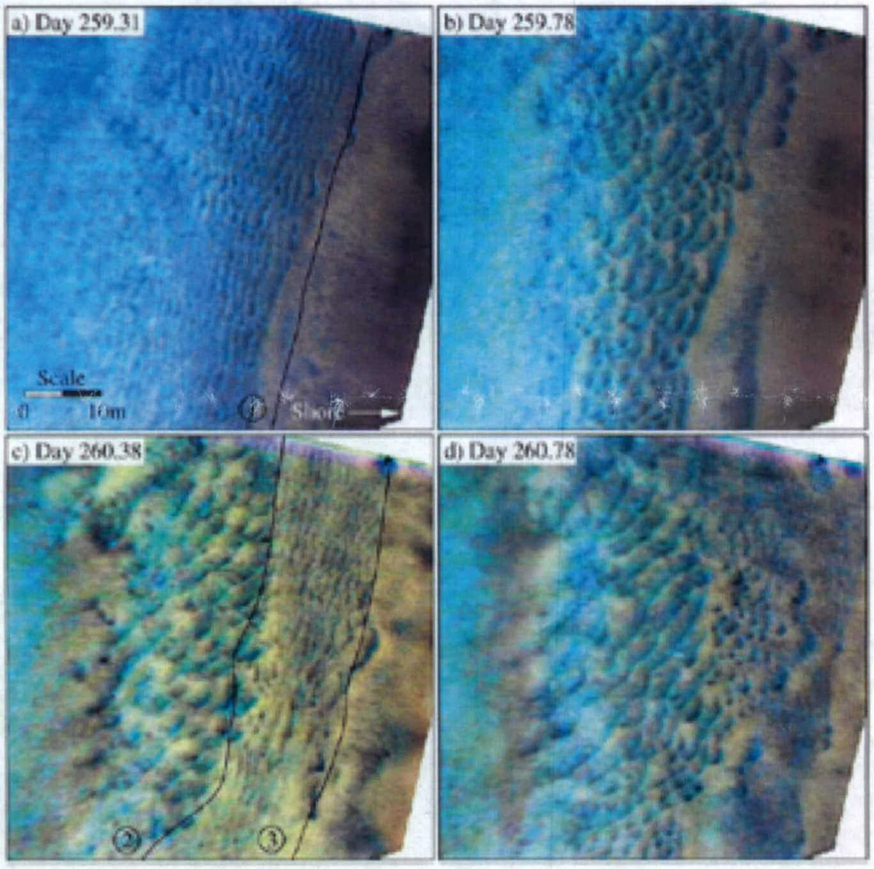
illustrated below:



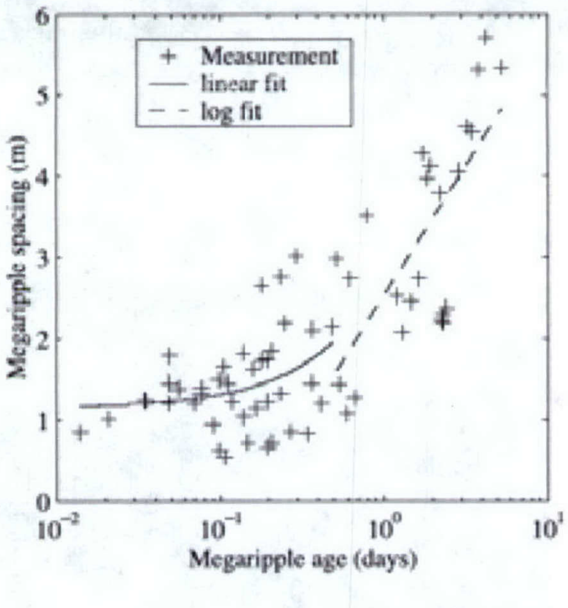
This technique was used to test a model for megaripple occurrence based on the idea that megaripples will always form in the surf zone if the conditions are not changing too fast (tide not changing too fast) and the megaripples are not destroyed as they move through the swash zone (Clarke and Werner, 2004). The test yields up to ~ 82% predictability of megaripple occurrence on Scripps Beach during 2000 (more than seven standard deviations above a random model prediction) but offshore wave parameters yield no statistically significant predictability during this period. For example, the distribution of time between predicted transitions from and to a state with megaripples and measured transitions is much narrower than for a model based on random transitions:



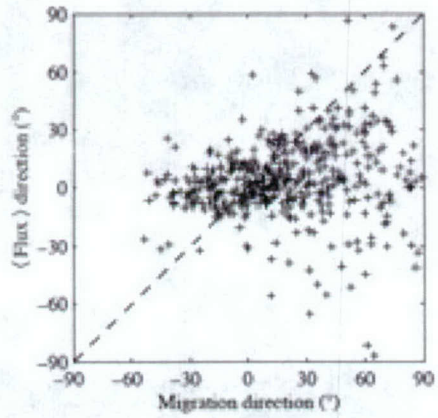
Despite the success of the model, megaripple configurations exhibit considerable complexity:



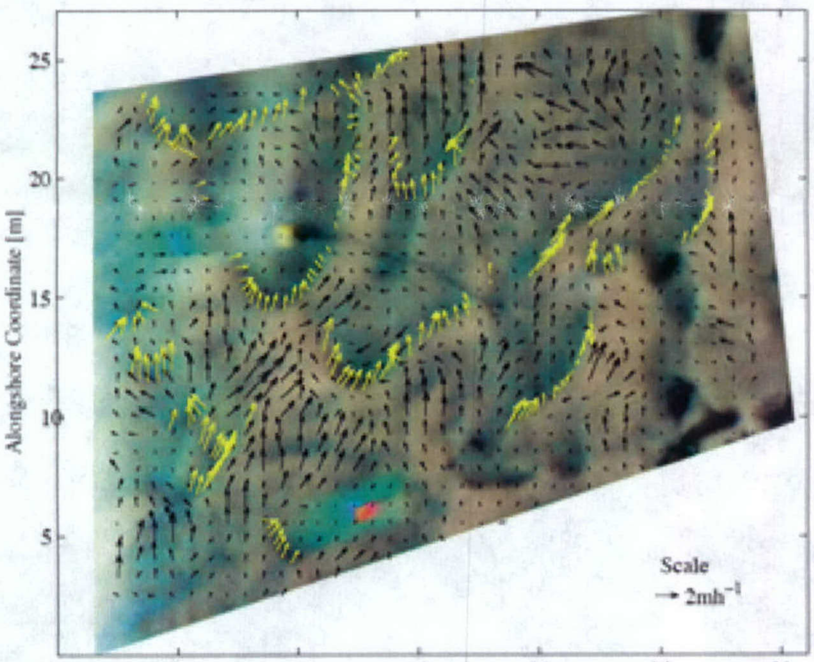
Observations of megaripple spacing versus age for this data set roughly follow the trend predicted by a model for bedform spacing based on defect dynamics, linear growth followd by logarithmic growth with time (Werner and Kocurek, 1999):



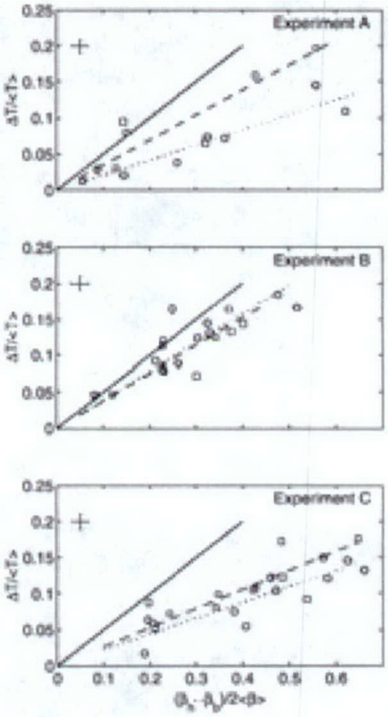
In a paper that is close to being submitted (Clarke and Werner, 2005), measurements of bedform orientation taken from the synoptic imaging technique are combined with measurements of fluid velocities from a surf zone sensor to compare predictions of bedform orientation models with measurements. Neither a model based on gross bedform normal transport nor a model based on defect dynamics makes statistically significant accurate predictions. The probable cause is a lack of significant correlation between migration direction and sediment flux predicted from measuring water velocity:



For any reasonable model for bedforms, including both orientation models, sediment flux direction and migration direction are the same. Therefore, we concluded that predictions of sediment flux based on water velocities well up in the water column over megaripples probably are highly inaccurate, because of flow modification by meagripples (whose heights often are a nonnegligible fraction of depth in the surf zone). Indeed, using migration of small bedforms as indicators of sediment flux over large megaripples, we found considerable complexity in flow patterns and migration:



In tests of self-organization during beach cusp formation, we found (Coco et al., 2003) that both the feedback of morphology on flow (below) and the feedback of flow on morphology could be detected:



Observations of morphology and flow during beach cusp formation indicated that beach cusps waned during rising tide and waxed during falling tide, possibly owing to groundwater effects.

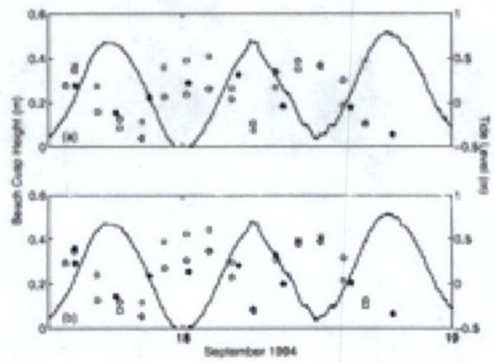
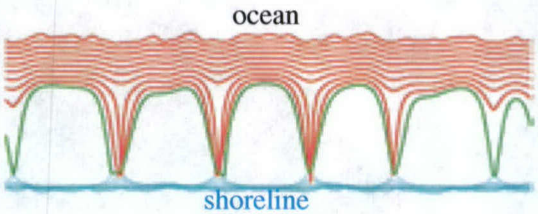


Figure 16. Beach cusp height as a function of time at elevation 0.8 m. Symbols are observations (stars) and numerical simulations with smoothing (squares) and smoothing and groundwater effects (circles) of experiment C for two horn-bay-horn systems centered at alongshore position (a) 780 m and (b) 840 m. The curve is tide level. Model runs were initialized with morphology from experiment C (09171320 and Figure 14a) and run for 28 hours.

Numerical simulations of beach cusps with groundwater infiltration and exfiltration reproduced many of the aspects of these observations.

In a model for sand bars, sand bar patterns are characterized by sand bar crestline position and height and by shoreline position. In this model, crescentic sand bars develop from a linear bar when sediment flux at the bar crest is onshore, with a sufficiently weak cross-shore variation so that onshore bar migration is unstable; a pattern of onshore-directed horns and embayments results, with spacing dictated by an interplay between unstable migration and along-crest smoothing, a reaction-diffusion mechanism (above, right). The shoreline reacts with a mirror-image pattern for wave-dominated onshore surf zone transport (above to the right) or with an offset mirror-image pattern with horns of bars opposite shoreline embayments for offshore current-dominated surf zone transport.



In a separate cross-shore model that includes bar formation at the shoreline and migration that accounts for the effect of multiple bars offshore, we reproduce the offshore migration and disappearance of sand bars in multiple bar systems, as observed, for example, off the Dutch coast. These two sand bar models are still being explored.

PUBLICATIONS

LB Clarke and BT Werner (2004) Tidally modulated occurrence of megaripples in a saturated surf zone, Journal of Geophysical Research, 109, C01012.

G Coco, TK Burnet, BT Werner and S Elgar (2003) The role of tides in beach cusp development, Journal of Geophysical Research, 109, C04011.

G Coco, TK Burnet, BT Werner and S Elgar (2003) Test of self-organization in beach cusp formation, Journal of Geophysical Research, 108, C3, 46-1--46-11.

LB Clarke and BT Werner (2003) Synoptic imaging of nearshore bathymetric patterns, Journal of Geophysical Research, 108, C1, 5-1--5-14.